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**LETTER**

# Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs

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## Abstract

Brazil plans to meet the majority of its growing electricity demand with new hydropower plants located in the Amazon basin. However, large hydropower plants located in tropical forested regions may lead to significant carbon dioxide and methane emission. Currently, no predictive models exist to estimate the greenhouse gas emissions before the reservoir is built. This paper presents two different approaches to investigate the future carbon balance of eighteen new reservoirs in the Amazon. The first approach is based on a degradation model of flooded carbon stock, while the second approach is based on flux data measured in Amazonian rivers and reservoirs. The models rely on a Monte Carlo simulation framework to represent the balance of the greenhouse gases into the atmosphere that results when land and river are converted into a reservoir. Further, we investigate the role of the residence time/stratification in the carbon emissions estimate. Our results imply that two factors contribute to reducing overall emissions from these reservoirs: high energy densities reservoirs, i.e., the ratio between the installed capacity and flooded area, and vegetation clearing. While the models' uncertainties are high, we show that a robust treatment of uncertainty can effectively indicate whether a reservoir in the Amazon will result in larger greenhouse gas emissions when compared to other electricity sources.

## 1. Introduction

The Brazilian energy plan states that, by 2022, 85% of new hydropower generation capacity (40 gigawatts) will come from hydroelectric power plants, set to be located in the Amazon region (MME EPE 2013). Supporters of this expansion claim that, among other benefits, hydropower is a low carbon source of electricity (MME EPE 2014). However, this idea has come under scrutiny, particularly for tropical forests reservoirs (St. Louis *et al* 2000, Barros *et al* 2011, Demarty and Bastien 2011, Wehrli 2011, Fearnside and Pueyo 2012). Specific hydropower reservoirs in the Amazon were reported to emit greenhouse gases (GHG) of the same order of magnitude as thermal power plants (Abril *et al* 2005, Santos *et al* 2006, Kemenes *et al* 2011).

One of the major issues that contribute to the controversy about GHG emissions from hydropower is the lack of established method to estimate future emissions. While there are estimates of carbon (C) emissions from specific hydropower reservoirs in tropical forests and their effect on the regional and global C budget (Abril *et al* 2005, Kemenes *et al* 2007, 2011, Barros *et al* 2011), previous work did not present methods to evaluate future emissions. Moreover, although the literature about the C balance in reservoirs has advanced considerably in the last decades, predicting the C budget for future reservoirs is still challenging because of the difficulty in representing the spatial and temporal variability of the C fluxes (Galy-Lacaux *et al* 1999, Roland *et al* 2010). Given the high number of dams planned in the Amazon region and in other countries like China, it is imperative to

develop models to estimate the C balance of large hydropower projects in order to support decision-making before the dam construction (Hu and Cheng 2013).

The GHG flux rates into the atmosphere from a tropical reservoir depend on a complex combination of physicochemical, meteorological, and reservoir features (St. Louis *et al* 2000, Abril *et al* 2005, Guérin *et al* 2006, Kemenes *et al* 2007, 2011, Barros *et al* 2011, Demarty and Bastien 2011, Fearnside and Pueyo 2012, Goldenfum 2012). Part of the difficulty of quantifying the C balance spatial and temporal variability of future reservoirs resides in an incomplete understanding of the physical, chemical, and biological processes involved in the production, consumption, and C outgas from reservoirs (Hu and Cheng 2013). For example, GHG production rate and C fate from flooded trunks is still undetermined (Guérin *et al* 2008).

Under this context of high uncertainty related to the C balance modeling, this paper presents a set of models, based on a Monte Carlo simulation structure, to explore the GHG emissions in tropical forested reservoirs. We investigate the GHG emission from new Amazon reservoirs using two approaches: top-down (TD) and bottom-up (BU). The TD approach is based on carbon dioxide ($CO_2$) and methane ($CH_4$) flux data measured in reservoirs and rivers located in the Amazon region. The BU approach relies on a degradation model based on the available carbon stock within the reservoir area. We then compare our results to the GHG emissions that would occur with other electricity generation sources.

## 2. Data and methods

### 2.1. GHG emissions from reservoirs and modeling overview

$CO_2$ and $CH_4$ emissions from hydropower result from the oxic/anoxic decomposition of the flooded organic matter (OM) from different sources within the reservoir (e.g. vegetation and soils, macrophytes, and algae produced in the reservoirs) and from outside the reservoir (e.g. sedimentary OM input from the upstream river basin) (Rosa *et al* 2004, Abril *et al* 2005, Guérin *et al* 2008). $CO_2$ is formed by bacterial respiration of OM in the soils, sediments, and water column but is also imported from upstream and lateral sources, such as drawdown zones (Guérin *et al* 2008). Further, $CO_2$ in freshwaters is produced by respiration and decomposition and assimilated by aquatic primary production (Cole *et al* 2007). $CH_4$ is produced in the reservoir's anaerobic zones by methanogenic bacteria, and can then be oxidized into $CO_2$ by methanotrophic bacteria in both the soils' aerobic zones (Guérin *et al* 2008, Bastviken 2009) and the water column (Lima 2005, Guérin and Abril 2007).

After production, $CO_2$ and $CH_4$ are released into the atmosphere through four major pathways:

(1) *Diffusion in the reservoir area*, which is the flux that occurs in the air–water interface of the reservoir due to the difference in gas concentrations at this layer (Cole and Caraco 1998).

(2) *Ebullition in the reservoir area* that results from the quick release of GHG from sediment pore waters supersaturated with $CH_4$ (DelSontro *et al* 2011).

(3) *Outlet degassing* that results from pressure and temperature changes that occur on discharge flows just after low-level outlets, such as turbines and spillways (Abril *et al* 2005, Kemenes *et al* 2007, 2011).

(4) *Diffusion and ebullition downstream of the dam*, which occur in the river area below the dam and are associated with the high concentrations of GHG from the reservoir hypolimnion (Abril *et al* 2005, Kemenes *et al* 2007).

The net GHG emissions in a river basin resulting from the creation of a reservoir should account for the balance between emissions and sinks in all parts of the watershed affected by the reservoir before and after the impoundment (Demarty and Bastien 2011, Kemenes *et al* 2011, Goldenfum 2012, Teodoru *et al* 2012). To estimate net GHG emissions we employed two approaches.

First, the TD approach relies on GHG flux data measured in tropical Amazonian reservoirs (Balbina, Petit Saut, Tucuruí, Samuel, and Santo Antônio) and rivers, which were used to model the various emission components: diffusion and bubbling from the reservoir, outlet degassing, diffusion and ebullition from downstream, and the natural river. Therefore, this model directly accounts for the major emission pathways into the atmosphere, and the difference between emissions before and after the reservoir flooding defines the net reservoir emissions.

Second, the BU approach is based on the potential emissions derived from the degradation of the flooded OM in the reservoir area, accounting for GHG production rates and $CH_4$ oxidation in the water column. Brazilian environmental rules require vegetation clearing of the flooded area before filling the reservoir (Kubistcheck 1960). However, biomass regrowth and inefficient clearing may increase the flooded C stock. In the BU approach, the net reservoir emissions are defined as the difference between (1) the $CO_2$ and $CH_4$ production from the degradation of the flooded C stocks (soils and remaining foliage), and (2) the $CH_4$ consumption and $CO_2$ production in the freshwater system by $CH_4$ oxidation. The BU model also accounts for the emissions from the vegetation that is cleared, which decays within the time horizon of this analysis.

In our framework, we assigned probability distributions for each of the uncertain variables in the models. Based on independent sampling from these distributions, each simulation corresponds to the

computation of a model outcome. We applied the models to new Amazon hydropower reservoirs, repeating each simulation 10 000 times.

## 2.2. Residence time (RT), stratification, and GHG emissions

Reservoir stratification occurs as a result of thermal differentials in the water column that prevent vertical water mixing. The reservoir stratification with an anoxic bottom layer creates the conditions for $CH_4$ accumulation in the hypolimnion (St. Louis *et al* 2000, Abril *et al* 2005). Old Amazonian reservoirs (Balbina, Samuel, Petit Saut and Tucuruí), where the GHG flux data that are the basis for the TD model were measured, stratify for long periods with intervals of complete mixing. The biogeochemical cycles in these reservoirs are strongly related to the decomposition of vegetation and anoxic conditions in the hypolimnion (Tundisi *et al* 1993).

Previous work has described the stratification process and its relation to RT. Typical lake stratification occurs in reservoirs with high RT ($>100$ days) (StrašKraba 1973; Straškraba *et al* 1993). This trend is consistent with the conditions at the Petit Saut reservoir, where there is a high positive correlation between RT, $CH_4$ concentrations, and emissions (Delmas *et al* 2001, Abril *et al* 2005). Further, the high levels of $CH_4$ concentrations in the hypolimnions are highly correlated with outlet degassing and downstream emissions (Guérin *et al* 2006). The main channel of reservoirs with low RT ($<10$ days), on the other hand, have characteristics that resemble a river zone: a completely mixed water column, with homogenous flow rate and temperature distribution (StrašKraba 1973, Straškraba *et al* 1993). This trend is consistent with the conditions in Santo Antônio reservoir (Fearnside 2015b). However, tributary and bay zones in low RT reservoirs may present different conditions and stratify because of lower water flows in these areas (Fearnside 2015b). Moreover, $CH_4$ oxidation efficiency also depends on the characteristics of the water column, such as light penetration (Dumestre and Guézennec 1999), turbulence (Guérin and Abril 2007), and reservoir depth (Lima 2005). Therefore, GHG fluxes in new Amazonian reservoirs will depend on their stratification level.

## 2.3. New Amazonian hydroelectric reservoirs

We assessed $CO_2$ and $CH_4$ emissions of 18 reservoirs recently built, under construction, or planned in eight rivers in the Amazon basin, corresponding to a total of 5900 km$^2$ of reservoir area and a total installed capacity of 40 GW (table 1). The design characteristics of the hydropower plants come from engineering reports provided by the Brazilian Electric Agency (Agência Nacional de Energia Elétrica—ANEEL). For each reservoir, we then cross-referenced the spatial location data of the reservoir shape with high-resolution maps of land surface, permanent water bodies, and forest biomass density in order to estimate the reservoir and river areas, and the biomass C stock in the reservoir area (Saatchi *et al* 2008, Hansen *et al* 2013). The supporting information (SI) provides a detailed explanation of the method used to estimate the reservoir and river areas.

## 2.4. Model details

Two stages characterize the C emissions from hydroelectric reservoirs. During the first stage, decomposition of easily degradable biomass in the flooded area (like soil micro fauna and green parts of the vegetation) drives a sharp increase in emissions during the first few years. During the second phase, emissions tend to be slower as the system reaches a steady state (Galy-Lacaux *et al* 1999, St. Louis *et al* 2000, Rosa *et al* 2004, Demarty and Bastien 2011). Our model accounts for both stages as described further in this section.

To account for the influence of water column conditions on reservoirs emissions, we developed separate TD models for stratified reservoirs (high RT) and well-mixed reservoirs (low RT) in our database. To assess the stratification level of each reservoir, we performed an analysis of the Densimetric Froude number, which is a more accurate criterion for the development of stratification compared to the RT alone (Straškraba *et al* 1993). We classified the characteristics of each reservoir according to their operating characteristics, RT, and propensity to stratify. Based on this analysis, which we described in more detail in the SI, we suggest that Cachoeira dos Patos, Cachoeira do Caí, Sinop, and Jamanxim are reservoirs with high RT and long periods of stratification, and they are assumed to behave similarly to the older reservoirs from which C flux data have been collected. All the other reservoirs in our database have well-mixed water columns with low RT throughout the year, and the main channel will thus resemble the emissions of natural rivers. Tributaries and bays in these low RT reservoirs, however, stratify and thus result in emissions that are similar to those of the high RT reservoirs.

The BU model, on the other hand, relies on a degradation model based on the flooded and cleared C stock in the reservoir area. Table 2 provides a summary of the models' variables and major assumptions.

### 2.4.1. BU approach.

We present a mass balance to estimate net reservoir emission using $CO_2$ and $CH_4$ production rates derived from incubation of soils and foliage from the Petit Saut reservoir (Guérin *et al* 2008). The initial flooded C stock is defined by the multiplication of the flooded area (discounting the natural river area) and the soil/foliage OM C density. Additionally, we account for the fate of the cleared biomass C stock for each reservoir based on above the ground biomass distribution map (Saatchi *et al* 2008). We assumed that C of the cleared

**Table 1.** Characteristics of hydroelectric reservoirs included in this study. Table S8 in the SI present the detailed data source from ANEEL for each project.

| Hydroelectric power plant | River | Power (MW) | Capacity factor | Reservoir area: (km$^2$) | Reservoir operation | Volume (×106 m$^3$) | Mean flow (m$^3$ s) | Mean depth (m) | Power density (MW km$^2$) | Water type[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| Belo Monte | Xingu | 11 233 | 0.41 | 516 | run-of-river | 4570 | 7800 | 9 | 21.8 | Clear |
| Bem Querer | Branco | 708 | 0.55 | 559 | run-of-river | 2530 | 3000 | 5 | 1.3 | Clear |
| Cachoeira do Caí | Jamanxim | 802 | 0.51 | 420 | storage | 3420 | 1940 | 8 | 1.9 | Clear |
| Cachoeira do Caldeirão | Araguari | 219 | 0.56 | 48 | run-of-river | 231 | 930 | 5 | 4.6 | Clear |
| Cachoeira dos Patos | Jamanxim | 528 | 0.32 | 117 | storage | 696 | 1330 | 6 | 4.5 | Clear |
| Colíder | Teles Pires | 300 | 0.56 | 172 | run-of-river | 1520 | 943 | 9 | 1.7 | Clear |
| Ferreira Gomes | Araguari | 252 | 0.60 | 18 | run-of-river | 137 | 963 | 8 | 14.2 | Clear |
| Jamanxim | Jamanxim | 881 | 0.53 | 74 | storage | 1000 | 1370 | 13 | 11.8 | Clear |
| Jatobá | Tapajós | 2338 | 0.55 | 646 | run-of-river | 4010 | 10 400 | 6 | 3.6 | Clear |
| Jirau | Madeira | 3750 | 0.58 | 303 | run-of-river | 2750 | 17 900 | 9 | 12.4 | White |
| Marabá | Tocantins | 1850 | 0.63 | 1024 | run-of-river | 5350 | 10 300 | 5 | 1.8 | Clear |
| Salto Augusto de Baixo | Juruena | 1461 | 0.54 | 125 | run-of-river | 362 | 4120 | 3 | 11.7 | Clear |
| Santo Antônio | Madeira | 3150 | 0.65 | 271 | run-of-river | 2080 | 18 200 | 8 | 11.6 | White |
| São Luís do Tapajos | Tapajós | 6133 | 0.52 | 722 | storage | 7550 | 11 900 | 10 | 8.5 | Clear |
| São Manoel | Teles Pires | 746 | 0.49 | 64 | run-of-river | 577 | 2260 | 9 | 11.7 | Clear |
| Sao Simão Alto | Juruena | 3509 | 0.55 | 284 | run-of-river | 3820 | 4190 | 13 | 12.4 | Clear |
| Sinop | Teles Pires | 461 | 0.43 | 330 | storage | 3070 | 894 | 8 | 1.4 | Clear |
| Teles Pires | Teles Pires | 1820 | 0.54 | 152 | run-of-river | 905 | 2410 | 6 | 12.0 | Clear |

[a] The water type classification is based on the map elaborated by Junk *et al* (2011).

**Table 2.** Summary of the modeling assumptions.

| | Uncertain variables | Major assumptions |
|---|---|---|
| **Bottom-up** | | |
| | • Flooded carbon stock in the soils and foliage | We assumed a uniform distribution that varies from 8 to 16 Gg C km$^{-2}$ for $0-20$ cm layer to define the carbon stock in the soils (Cerri *et al* 2007). We also assumed that an inefficient biomass clearing contributes to an additional flooded carbon stock from foliage that varies from 0.6 to 6.4 C km$^{-2}$ (Malhi *et al* 1999). |
| | • Carbon stock from cleared biomass | |
| | • $CO_2/CH_4$ production | |
| | • $CH_4$ oxidation | We explored a $CH_4$ oxidation fraction range that varies from 45% to 95% of the methane production (Angelis and Scranton 1993, Guérin and Abril 2007, Kemenes *et al* 2007, Bastviken 2009) |
| | • $CO_2$ production from $CH_4$ oxidation (bacteria efficiency growth) | |
| **Top-down** | | |
| High RT | • Reservoir diffusion and ebullition | Based on emissions fluxes from classical 'old' reservoirs of Tucuruí, Petit Saut, Samuel, and Balbina, which have high RT and present long periods of stratification throughout the year (Fearnside 2002, Abril *et al* 2005, Guérin *et al* 2006, Santos *et al* 2006, Kemenes *et al* 2007). |
| | • Outlet degassing | |
| | • Downstream diffusion and bubbling | |
| | • Natural emissions | |
| Low RT | • Reservoir diffusion and bubbling | We divided the reservoir area in two regions: |
| | • Natural emissions | The main channel zone has well-mixed water columns and limnological characteristics similar to river zones. Therefore, the probability distributions adopted for the reservoir fluxes in this model rely on the fluxes data from large natural rivers in the Amazon. |
| | • Degassing/downstream (parametrically) | The bays and tributaries zones have stratified conditions and probability distributions used are based on the emissions fluxes from classical 'old' reservoirs. |
| | | Degassing/downstream emissions in these reservoirs are based on Santo Antônio reservoir data (Fearnside 2015b). We treated this pathway parametrically because only one estimate is available. See the SI for details. |

biomass decays in a period of 30 years and is released to the atmosphere as $CO_2$ (see SI for a more detailed discussion about the fate of cleared biomass, pages 24 to 25).

We calculated GHG production using monthly times steps and production rates sampled from distributions based on the mean and standard deviation of GHG potential production rates obtained from soil/foliage incubation from Petit Saut reservoir (Guérin *et al* 2008). We assumed that $CH_4$ production rates are the same for both low and high RT models because most of the organic C in the saturated soil/water layers is expected to be in similar anoxic environments. $CH_4$ oxidation is treated as a fraction of the $CH_4$ produced from soils/foliage (see table 2). $CH_4$ oxidation results in $CO_2$ production and we assume that bacterial growth efficiency has a triangular distribution that ranges from 10% to 80% with the most probable value at 50%.

*2.4.2. TD approach*

In the TD approach, we divided the GHG emissions in two systems: the river system (before flooding) and the reservoir system (after flooding). Using reservoir shape data, we identified the beginning of the reservoir at the upstream side (upstream limit) and extended the

model boundary to cover C fluxes that occur up to a 40 km river distance downstream the dam (downstream limit).

The river system represents the environment before the construction of the reservoir; in other words, the model accounts for the natural fluxes in Amazonian rivers. Rivers and wetlands in the Amazon are natural C sources as they transport, respire, and outgas C originating from OM from upland and flooded forests. For this paper, we performed a meta-analysis of published $CO_2$ and $CH_4$ fluxes in Amazon rivers (Rasera *et al* 2008, Alin *et al* 2011, Ellis *et al* 2012, Salimon *et al* 2012, Rasera *et al* 2013, Sawakuchi *et al* 2014) and classified the measurements by spatial location, water-chemistry type, and river size. Based on this database, we fitted statistical distributions to represent the variability of GHG fluxes in large Amazon Rivers (width greater than 100 m) according to water type: *black water* is associated with a high content of humic compounds; *white water* is associated with a high content of suspended sediment; and *clear water* is characterized by the lack of turbidity caused by sediments and a dark color caused by humic compounds (Furch 1984, Junk *et al* 2011).

The reservoir system characterizes the environment after the construction of the dam and consists of

**Table 3.** Summary of flux data ($n$ = data points).

| Emission source | mg $CH_4$ $m^{-2}$ $d^{-1}$ | | | mg $CO_2$ $m^{-2}$ $d^{-1}$ | | | References |
|---|---|---|---|---|---|---|---|
| | Mean | Range | $n$ | Mean | Range | $n$ | |
| **Rivers** | | | | | | | |
| White | 10 | 0−160 | 214 | 20 000 | 680−54 000 | 26 | (A) |
| Clear | 70 | 2−650 | 165 | 5900 | −760−24 000 | 42 | (A) |
| Black | 10 | 0−53 | 73 | 22 000 | 5700−48 000 | 27 | (A) |
| **Reservoirs** | | | | | | | |
| Reservoir | 50 | 0−210 | 20 | 8000 | 1500−43 000 | 15 | (B) |
| Degassing | 220 | 50–900 | 9 | 70 | 50–90 | 6 | (C) |
| Downstream | 1100 | 190–1800 | 7 | 35 000 | 18 000−66 000 | 7 | (C) |

Note: (A) (Rasera *et al* 2008, Alin *et al* 2011, Ellis *et al* 2012, Salimon *et al* 2012, Rasera *et al* 2013, Sawakuchi *et al* 2014), (B) (Delmas *et al* 2001, Fearnside 2002, Abril *et al* 2005, Lima 2005, Guérin *et al* 2006, Santos *et al* 2006, Kemenes *et al* 2007, 2011), (C) (Guérin *et al* 2006, Kemenes *et al* 2007, 2011).

reservoir surface, degassing, and downstream fluxes. The differences in the fluxes into the atmosphere between the reservoir system and the river system define the reservoirs' net GHG emissions. We estimated $CO_2$ and $CH_4$ emissions for both systems. Using available data (described in table 3), we fit several distribution functions to represent the flux rates' uncertainty and variability for each of the modeled pathways. The SI provides detailed information about these distributions.

The flux data we used in this paper was collected years after the reservoirs started operations, so we assumed that our sample represents the behavior of the reservoir system in a steady state. We also assumed that natural rivers are in a steady state of emissions. We then chose the best distribution for each flux rate through the calculation of the Bayesian Information Criterion and Akaike Information Criterion (Kuha 2004). We multiplied the specific flux and the associated surface area to define the total annual fluxes of $CO_2$ and $CH_4$ for each emissions pathway. Based on the emissions profile of Petit Saut in the first ten years, we then modeled the first pulse of emissions by applying a multiplier factor to the steady state emissions for the reservoir system (three times for the first three years, and two times for the fourth and fifth years). Finally, we converted $CH_4$ emissions to the equivalent $CO_2$ emissions using the 20 and 100 year $CH_4$ global warming potential of 86 and 34, respectively (IPCC *et al* 2013).The SI includes the detailed mathematical formulation of the models.

## 3. Results and discussion

Figure 1 presents the summary of the mean and 95% confidence interval (CI) of net GHG emissions over 100 years that result from 10 000 simulations for each modeling approach for each assessed reservoir. The simulations reveal a high variability of fluxes across the dams as a consequence of the site-specific characteristics of each project (reservoir area, river areas, and water type), as well as modeling assumptions. Mean net GHG emissions for all reservoirs over 100 years vary from 90 Tg of C (CI: 80–100) in the BU approach to 340 Tg of C (CI: 210–520) in the TD approach.

The emission results from the BU model shown in figure 1 are based on the initial soils and biomass C stock in the reservoir area. They represent lower bound estimates because C inputs from upstream and primary production in the reservoir are not included. Compared to the emissions from soils only, flooded foliage contributes to an average increase in $CH_4$ and $CO_2$ emissions of 33% and 28%, respectively. This result demonstrates the importance of the enforcement and improvement of vegetation clearing as a GHG emissions mitigation measure, as discussed in more detail in the SI.

### 3.1. Low RT reservoirs
In the case of the low RT reservoirs, figure 1 shows that mean net GHG emissions over 100 years from the BU model range from 0.1 (CI: 0–0.2) Tg of C in Ferreira Gomes to 14 (CI: 10–17) Tg of C in Marabá. Mean TD estimates vary from 1 (CI: 0–3) Tg of C in Ferreira Gomes to 49 (CI: 5–160) Tg of C in Marabá. The BU method is based on a decreasing degradation function for the OM in the soils, residual foliage, and cleared vegetation (fixed initial C stock), while the TD model accounts for fluxes derived from freshwater systems. The TD fluxes were measured in the air–water interface and, thus, also account for other C inputs (e.g. upstream and lateral C inputs, and OM from primary production) (Richey *et al* 2002, Abril *et al* 2005, Guérin *et al* 2008). As a result, the mean results in the TD approach are on average four times higher than the mean results in the BU approach. Both approaches, however, result in estimates within the same order of magnitude. Average $CH_4$ emissions have the same order of magnitude for both approaches, but the uncertainty from the TD method is higher due to the characteristics of the statistical distributions adjusted in this model, which are right-skewed and have a long tail.
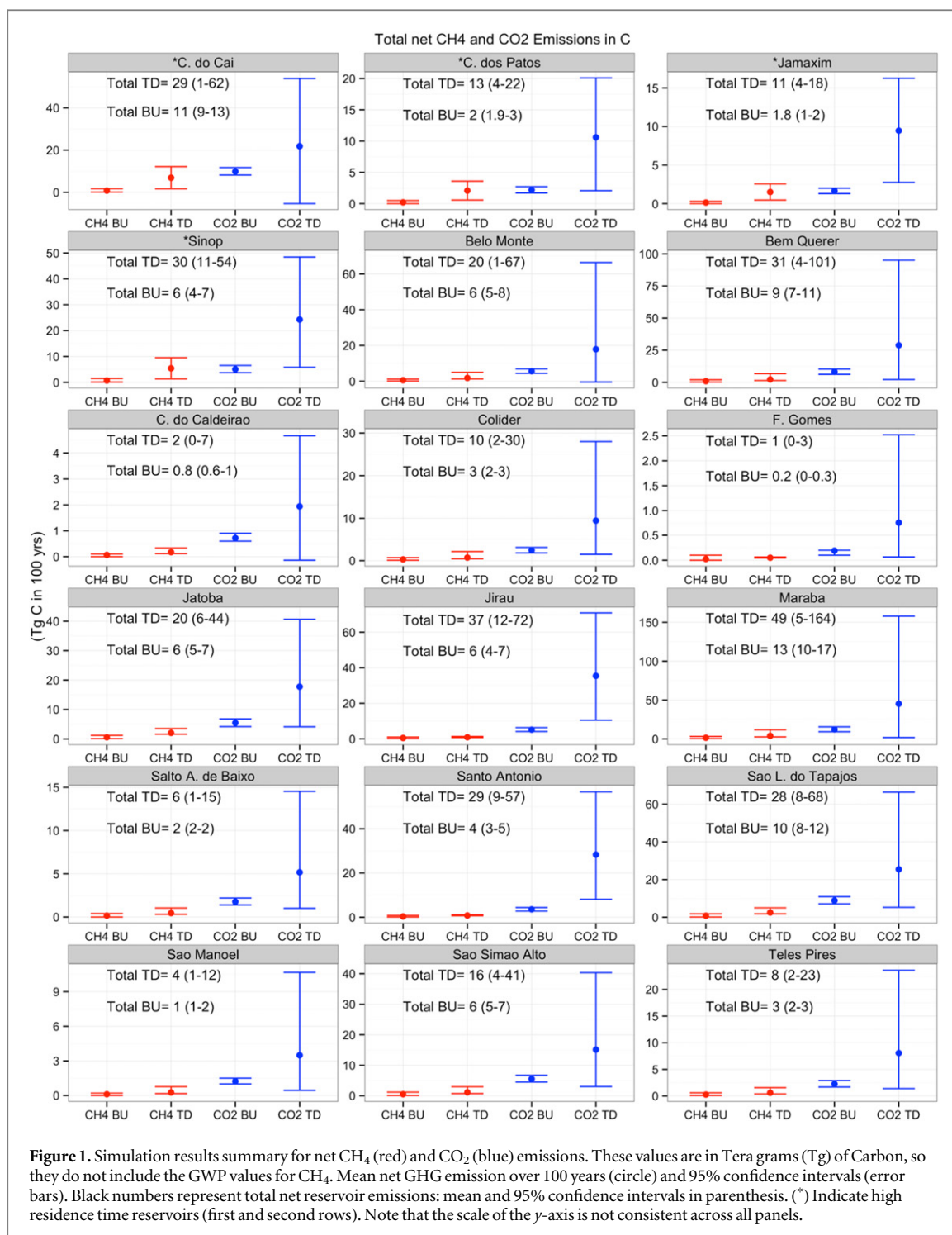
**Figure 1.** Simulation results summary for net CH$_4$ (red) and CO$_2$ (blue) emissions. These values are in Tera grams (Tg) of Carbon, so they do not include the GWP values for CH$_4$. Mean net GHG emission over 100 years (circle) and 95% confidence intervals (error bars). Black numbers represent total net reservoir emissions: mean and 95% confidence intervals in parenthesis. (*) Indicate high residence time reservoirs (first and second rows). Note that the scale of the *y*-axis is not consistent across all panels.

Figure S12 in the SI highlights the contribution of each pathway to the total C budget from the TD model.

### 3.2. High RT reservoirs

For high RT reservoirs, the BU approach indicates that the mean net GHG emissions over 100 years vary from 1.8 (CI: 1–2) Tg of C in Jamanxim to 11 (CI: 9–13) Tg of C in Cachoeira do Caí (figure 1). The mean results in the TD model are one order of magnitude higher compared to the BU outcomes and vary from 11 (CI: 4–18) Tg of C in Jamanxim to 30 (CI: 11–54) Tg of C in Sinop. Again, this difference is a result of the distinctive

methods employed for each approach. The BU model relies on a decreasing degradation function and provides a lower bound estimate that only accounts for the initial C stock in the reservoir area. In contrast, the TD approach relies on flux data measured in reservoirs where the above the ground biomass was not cleared. Thus, the TD approach accounts for fluxes into the atmosphere that derive from all inputs, including below and above-the-ground C stocks, as well as C imports from upstream and reservoir primary production.

New reservoirs in Brazil can only be filled after vegetation clearing (Kubistcheck 1960,

Fearnside 2015b), which did not occur in Petit Saut, Balbina, Tucuruí and Samuel. As a result, while the BU estimates are downward biased (underestimates), the TD approach is upward biased (overestimates) for high RT reservoirs. At this time, we are unable to assess the size of this bias, because we cannot distinguish between flooded, terrestrial, and aquatic inputs and their specific contribution to GHG emissions. This also justifies the use of two modeling approaches; merging them would leads to the risk of double counting. We propose, however, that the BU and TD results provide a range of plausible emissions from these reservoirs.

Figure 2 breaks down the contribution of each emission pathway to the net emissions (mean) for the TD approach in high RT reservoirs. For these reservoirs, we present the gross fluxes from the reservoir system (figures 2(A), (C) and (E), after flooding) and the natural river system (figures 2(B), (D) and (F), before flooding). In terms of C mass (figures 2(A) and (B)), $CO_2$ emissions from the reservoir, downstream emissions, and $CO_2$ fluxes from the natural river are the largest contributors to C fluxes. On the other hand, when including the 20 year and 100 year GWP as a metric for climate impacts, figures 2(C) and (E) show that $CH_4$ emissions account for most of the total Tera grams of $CO_2$ equivalents. In the mean scenario, natural emissions before the impoundment account for 5%–30% of the reservoir system emissions (comparing figures 2(A) and (B)), highlighting the importance of accounting for this natural emission pathway in the net C balance of Amazonian reservoirs.

Figure S12 in the SI shows similar results for the low RT reservoirs. While the magnitude of emissions varies significantly across reservoirs, figure S12 highlights the same trends observed for high RT reservoirs in figure 2: $CH_4$ emissions after the impoundment and natural emissions are critical components of the net C balance of these reservoirs. The main advantage of low RT reservoirs compared to high RT is the lack of stratification in the main channel. As a consequence, low RT reservoirs have lower average emissions from the reservoirs' surface in the main channel itself, as well as lower degassing/downstream fluxes. However, the major driver for high total GHG emissions is the size of the reservoir area. For example, Marabá is a low RT reservoir but resulted in the highest total GHG emissions over 100 years, because this reservoir has the greatest reservoir area from our database.

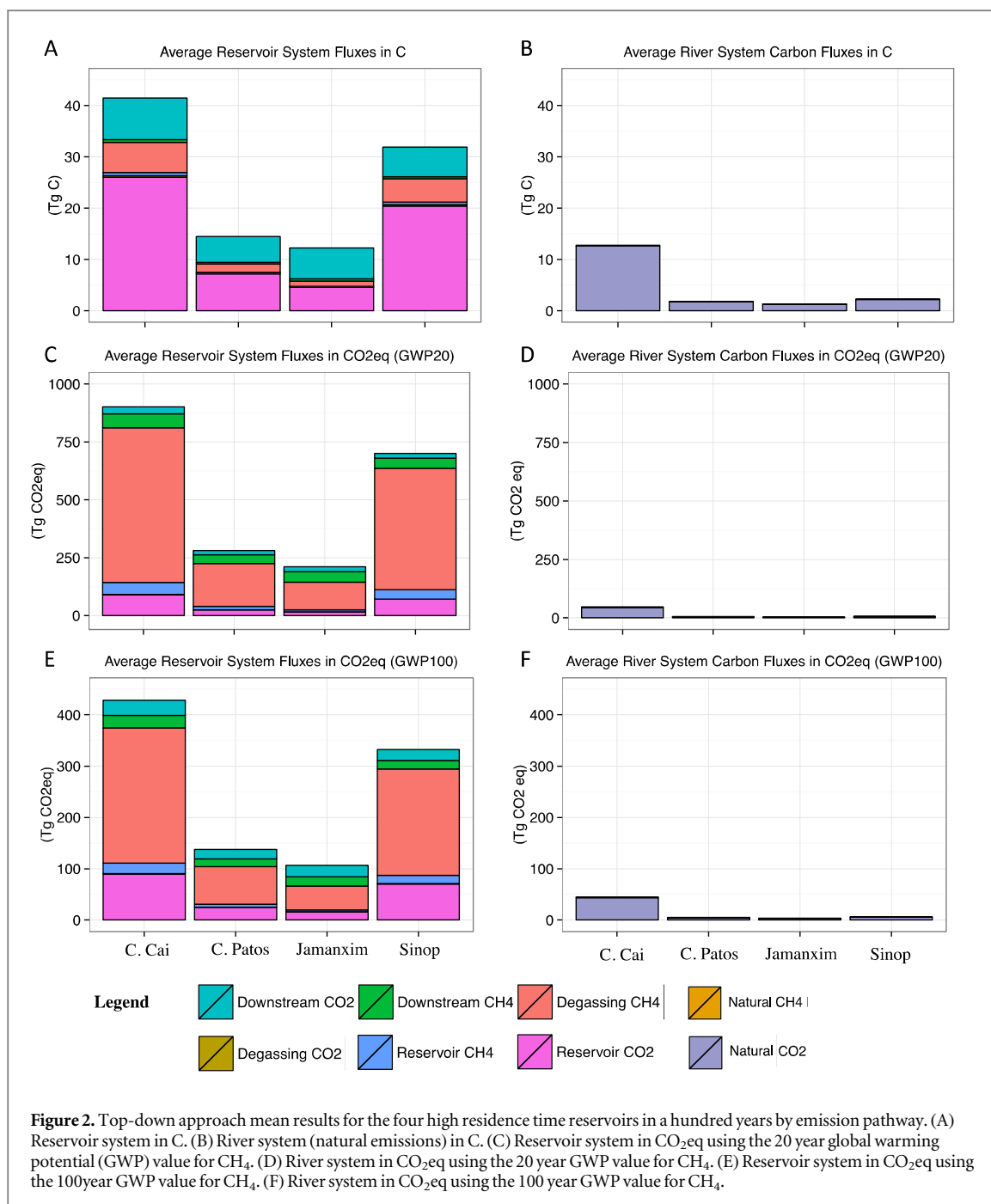### 3.3. Emission factors: hydropower in the Amazon versus other sources of electricity

To compare our results from hydropower plants in the Amazonian basin with other electricity generation sources, we calculated the emission factor for each reservoir in units of kg $CO_2$eq MWh$^{-1}$ (figure 3). As before, the results include the 20 year and 100 year GWP for $CH_4$. We used a meta-analysis from the Intergovernmental Panel on Climate Change (IPCC)

with life cycle assessment studies as a reference to compare our results with other sources of electricity (Moomaw *et al* 2011). This literature indicates that the median emission factors for natural gas, oil, and coal-based power plants are 470, 840, and 1000 kg $CO_2$eq MWh$^{-1}$, respectively (Moomaw *et al* 2011). In the case of renewables, the median emission factors are 4, 12, and 46 kg $CO_2$eq MWh$^{-1}$ for hydropower, solar (photovoltaic) and wind, respectively. This comparison is not meant to be a recommendation about the source of energy Brazil should pursue, as such recommendation requires much more detailed analysis about the entire power system that is beyond the scope of this paper.

Figure 3 shows that six of the reservoirs (Cachoeira do Caí, Cachoeira dos Patos, Sinop, Bem Querer, Colider and Marabá) have a significant number of simulations that result in emission factors that are comparable to those of thermal power plants. The simulation results confirm that using life cycle emission estimates from hydropower currently available in the IPCC report to aid decision-making may result in unintended consequences (Fearnside 2015a).

It is noteworthy that figure 3 shows that high RT reservoirs have higher simulated emission factors compared to thermal power plants. Even though we concluded that the TD approach overestimates GHG emissions for new high RT reservoirs, combined with the lower bound estimates from the BU approach, we can gather useful information to understand the potential range of GHG emissions in new reservoirs. For example, the results indicate that Jamanxim reservoir likely has a lower emission factor than thermal power plants, because of the dominance of simulation results below the natural gas power plants reference value. In contrast, most of the simulated emission factors for Cachoeira dos Patos, Cachoeira do Caí, and Sinop are higher than those for thermal power plants.

Moreover, it is worth highlighting that because of the higher GWP for $CH_4$ over 20 years, the simulation results using this GWP are higher and suggest the hydropower emissions could have serious climate impacts in the short-term. The SI presents the emission factor simulation results by reservoir age. During the first three years of operation, all new hydropower plants in the Amazon have at least some emission factor outcomes above or at the natural gas generation level (see tables S22 and S23 in the SI). While GWP can serve as a proxy for climate impacts, recent studies suggest it can be an imperfect metric for policy analysis (Shine *et al* 2005, Shine 2009, Peters *et al* 2011, Kendall 2014). In this paper, for example, using GWP implicitly assumes that the emissions over the entire life of these projects (100 years) occur as a pulse emission in year 0. Thus, the values in this study do not account for the timing of emissions. Hence, this paper should not be the basis for statements about the global climate impacts of large reservoirs, such as the effect on global temperatures. The results in this paper,

**Figure 2.** Top-down approach mean results for the four high residence time reservoirs in a hundred years by emission pathway. (A) Reservoir system in C. (B) River system (natural emissions) in C. (C) Reservoir system in $CO_2$eq using the 20 year global warming potential (GWP) value for $CH_4$. (D) River system in $CO_2$eq using the 20 year GWP value for $CH_4$. (E) Reservoir system in $CO_2$eq using the 100year GWP value for $CH_4$. (F) River system in $CO_2$eq using the 100 year GWP value for $CH_4$.
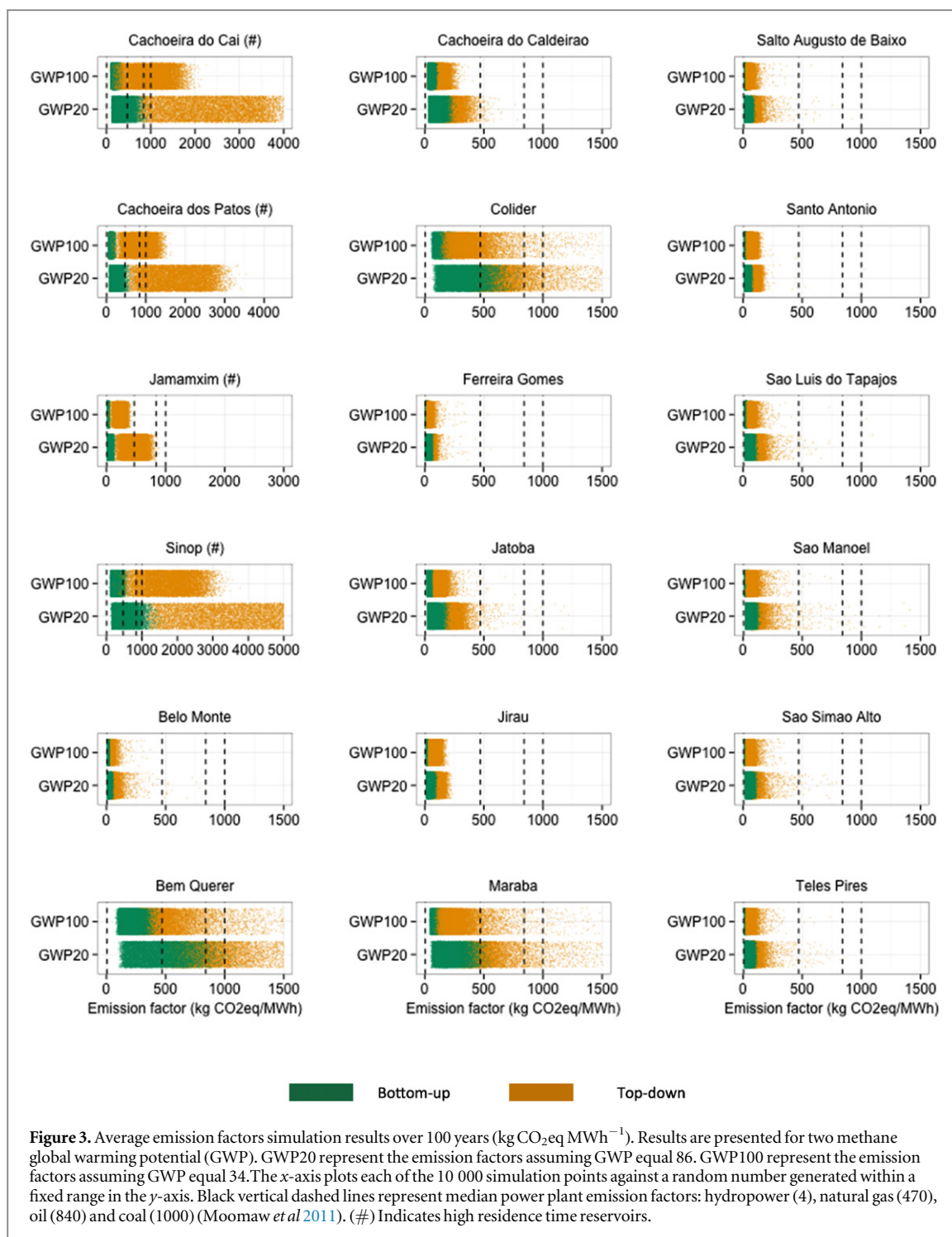
however, present an account of C emissions that could later be used to model such climate impacts, and future work will expand on this area of research.

Focusing on low RT reservoirs, the reservoirs of Bem Querer, Colider and Marabá have a high number of simulations that suggest these reservoirs have emissions factors larger than those of thermal power plants. In the case of the 20 year GWP results, the emission factors from the BU simulations are also high, consistent with the TD results. Further, Ferreira Gomes is the only reservoir with emission factors that are similar to those of solar and wind projects. In summary, figure 3 shows that a robust treatment of the uncertainty, which is possible by the application of the Monte Carlo simulation structure and the clear

statement of model assumptions, provides valuable information about each reservoir that can be used to support decision-making in most cases.

Another relevant difference worth noting between some of the old and new hydropower reservoirs in the Amazon is the relationship between flooded area and installed capacity (power density in MW km$^{-2}$). There is a strong negative correlation between the hydropower plant emission factors and its power density (Demarty and Bastien 2011). Reported emission factors for the old tropical reservoirs of Balbina, Tucuruí, Petit Saut, and Samuel are higher than those of fossil fuel power plants, with mean emission factors of 2200, 480, 1300, and 2200 kg $CO_2$eq per MWh, respectively (Demarty and Bastien 2011). The power densities of

**Figure 3.** Average emission factors simulation results over 100 years (kg $CO_2$eq MWh$^{-1}$). Results are presented for two methane global warming potential (GWP). GWP20 represent the emission factors assuming GWP equal 86. GWP100 represent the emission factors assuming GWP equal 34.The *x*-axis plots each of the 10 000 simulation points against a random number generated within a fixed range in the *y*-axis. Black vertical dashed lines represent median power plant emission factors: hydropower (4), natural gas (470), oil (840) and coal (1000) (Moomaw *et al* 2011). (#) Indicates high residence time reservoirs.

Balbina, Tucuruí, Petit Saut, and Samuel reservoirs are 0.1, 2.9, 0.4 and 0.4 MW km$^{-2}$, respectively. In contrast to these old reservoirs, 13 of the new projects studied in this paper have power densities greater than 3.5 MW km$^{-2}$ (see table 1). Not surprisingly, the reservoirs with the lower energy densities are also the projects with higher emissions factors in our estimates (see figure S13 and S14 in the SI). Additionally, three out of the five storage power plants in our database are in the highest emission factor group because the additional volume for water storage often requires more reservoir area, which leads to lower energy densities

and higher emission factors. The SI presents a sensitivity analysis about the effect of the reservoir area in our estimates for storage reservoirs.

## 4. Implications and uncertainty

Our results suggest that GHG emissions from hydroelectric reservoirs vary significantly across the different projects; these emissions could be higher than currently assumed and, under specific conditions, could even be comparable to those of fossil-based power

plants. Most of the reservoir simulations resulted in lower emission factors when compared to those of thermal power plants, but higher when compared to those of solar or wind projects. It is important to note that this comparison is based on the accounting of emissions over the life of the projects and is not meant to be an assessment of the actual climate impacts from these energy projects, which would require either the use of more detailed climate metrics than GWP or a climate model.

Nevertheless, the comparison of emission factors between hydropower plants in the Amazon and other sources of electricity suggests that the climate impacts from large scale development of Amazonian hydropower can be greater than has been suggested in the life cycle literature. Over a hundred years, the 18 new reservoirs in the Amazon would lead to a average total emissions that vary from 9 Tg of $CH_4$ and 81 Tg of $CO_2$ (BU approach) to 21 Tg of $CH_4$ and 310 Tg of $CO_2$ (TD approach). As a point of comparison, emissions from the US natural gas energy system totaled 10 Tg of $CH_4$ and 35 Tg of $CO_2$ in 2013 (EPA 2015). As the global community moves to mitigate global GHG emissions, the potential emissions from Amazonian reservoirs should be considered in the context of emissions from other alternatives.

The Brazilian government is currently evaluating whether to keep investing in low RT reservoirs due to the advantages of adding storage capacity to the electric system. The results in this paper suggest that the adoption of high energy density reservoirs contributes to reduce overall GHG emissions for hydropower plants. Thus, the proposal to shift towards construction of storage reservoirs with larger areas and higher RT could result in increased emissions from Amazonian projects. Furthermore, our results suggest that the current policy that requires vegetation clearing before reservoir flooding supports a significant reduction in GHG emissions from these projects and should be improved.

Moreover, climate change and deforestation in the Amazon are factors that may affect atmospheric and surface conditions in the future, which would affect GHG emissions from reservoirs. Studies suggest that one of the impacts from land use change and global warming will be changes in Amazon precipitation patterns (Malhi *et al* 2008). Shifts in the regional climate patterns can influence reservoir emissions by changing the heat balance and surface mixed layer dynamics of hydroelectric reservoirs (Curtarelli *et al* 2014). Any changes in precipitation and wind patterns can also affect emissions, as they are important factors to define gas exchange flux variability (Abril *et al* 2005). Because of the uncertainty and the lack of knowledge in modeling the correlation between climate patterns and GHG emissions from reservoirs, we are unable to quantify the magnitude of future climate and land use change in our estimates.

The challenge of evaluating net GHG emissions due to reservoir creation is complex because of high spatial and temporal variability and the multiple factors that can interfere in the production, consumption, and emissions of GHGs in tropical reservoirs. The scarcity of data, as well as the gaps in the knowledge about the physical, chemical, and biological processes involved, contribute to the difficulty in estimating the C budget of future reservoirs. Nevertheless, given the large number of hydropower dams that are planned in the Brazilian Amazon region, it is essential to use the available scientific information to develop methods to evaluate the potential GHG emissions from hydroelectric projects. While the uncertainties of our models are high, the simulations explore a vast range of GHG emission scenarios for each hydropower reservoir and provide information that is useful to support decision-making.

**Competing financial interests**

The authors declare no competing financial interests.

## References

Abril G, Guérin F, Richard S, Delmas R, Galy-Lacaux C, Gosse P, Tremblay A, Varfalvy L, dos Santos M A and Matvienko B 2005 Carbon dioxide and methane emissions and the carbon budget of a 10 year old tropical reservoir (Petit Saut, French Guiana) *Glob. Biogeochemical Cycles* **19** 1–16

Alin S R, Rasera M de F F L, Salimon C I, Richey J E, Holtgrieve G W, Krusche A V and Snidvongs A 2011 Physical controls on carbon dioxide transfer velocity and flux in low-gradient river systems and implications for regional carbon budgets *J. Geophys. Res.* **116** G01009

Angelis M A and Scranton M I 1993 Fate of methane in the Hudson River and estuary *Glob. Biogeochemical Cycles* **7** 509–23

Barros N, Cole J J, Tranvik L J, Prairie Y T, Bastviken D, Huszar V L M, del Giorgio P and Roland F 2011 Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude *Nat. Geosci.* **4** 593–6

Bastviken D 2009 Methane *Encyclopedia of Inland Waters* ed G E Likens (New York: Academic) pp 783–805

Cerri C E P *et al* 2007 Predicted soil organic carbon stocks and changes in the Brazilian Amazon between 2000 and 2030 *Agric. Ecosystems Environ.* **122** 58–72

Cole J J and Caraco N F 1998 Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of $SF_6$ *Limnology Oceanogr.* **43** 647–56

Cole J J *et al* 2007 Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget *Ecosystems* **10** 172–85

Curtarelli M P, Ogashawara I, Araújo C A S, Alcântara E H, Lorenzzetti J A and Stech J L 2014 Influence of summertime mesoscale convective systems on the heat balance and surface mixed layer dynamics of a large Amazonian hydroelectric reservoir' *J. Geophys. Res.: Oceans* **119** 8472–94

Delmas R, Galy-Lacaux C and Richard S 2001 Emissions of greenhouse gases from the tropical hydroelectric reservoir of Petit Saut (French Guiana) compared with emissions from thermal alternatives *Glob. Biogeochemical Cycles* **15** 993–1003

DelSontro T, Kunz M J, Kempter T, Wüest A, Wehrli B and Senn D B 2011 Spatial heterogeneity of methane ebullition in a large tropical reservoir *Environ. Sci. Technol.* **45** 9866–73

Demarty M and Bastien J 2011 GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: review of 20 years of $CH_4$ emission measurements *Energy Policy* **39** 4197–206

Dumestre J F and Guézennec J 1999 Influence of light intensity on methanotrophic bacterial activity in Petit Saut Reservoir, French Guiana *Appl. Environ. Microbiol.* **65** 534–9

Ellis E E, Richey J E, Aufdenkampe A K, Krusche A V, Quay P D, Salimon C and Brandão da Cunha H 2012 Factors controlling water-column respiration in rivers of the central and Southwestern Amazon Basin *Limnology Oceanogr.* **57** 527–40

EPA (Environmental Protection Agency) 2015 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2013* (www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf)

Fearnside P M 2002 Greenhouse gas emissions from a hydroelectric reservoir (Brazil Tucurui Dam) and the energy policy implications *Water Air Soil Pollut.* **133** 69–96

Fearnside P M and Pueyo S 2012 Greenhouse-gas emissions from tropical dams *Nat. Clim. Change* **2** 382–4

Fearnside P M 2015a Emissions from tropical hydropower and the IPCC *Enviro. Sci. Policy* **50** 225–39

Fearnside P M 2015b Tropical hydropower in the clean development mechanism: Brazil's Santo Antônio dam as an example of the need for change *Clim. Change* **131** 575–89

Furch K 1984 *Water Chemistry of the Amazon Basin: The Distribution of Chemical Elements Among Freshwaters* ed H J Dumont and H Sioli (Dordrecht: Monographiae Biologicae) pp 167–99

Galy-Lacaux C, Delmas R, Kouadio G, Richard S and Gosse P 1999 Long-term greenhouse gas emissions from hydroelectric reservoirs in tropical forest regions *Glob. Biogeochemical Cycles* **13** 503–17

Goldenfum J A 2012 Challenges and solutions for sssessing the impact of freshwater reservoirs on natural GHG emissions *Ecohydrology Hydrobiology* **12** 115–22

Guérin F, Abril G, Richard S, Burban B, Reynouard C, Seyler P and Delmas R 2006 Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers *Geophys. Res. Lett.* **33** L21407

Guérin F and Abril G 2007 Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir *J. Geophys. Res.* **112** G03006

Guérin F, Abril G, de Junet A and Bonnet M P 2008 Anaerobic decomposition of tropical soils and plant material: implication for the $CO_2$ and $CH_4$ budget of the Petit Saut Reservoir *Appl. Geochemistry* **23** 2272–83

Hansen M C *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3

Hu Y and Cheng H 2013 The urgency of assessing the greenhouse gas budgets of hydroelectric reservoirs in China *Nat. Clim. Change* **3** 708–12

IPCC 2013 *Climate Change 2013 The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press)

Junk W J, Piedade M T F, Schöngart J, Cohn-Haft M, Adeney J M and Wittmann F 2011 A classification of major naturally-occurring Amazonian lowland wetlands *Wetlands* **31** 623–40

Kemenes A, Forsberg B R and Melack J M 2007 Methane release below a tropical hydroelectric dam *Geophys. Res. Lett.* **34** L12809

Kemenes A, Forsberg B R and Melack J M 2011 $CO_2$ emissions from a tropical hydroelectric reservoir (Balbina, Brazil) *J. Geophys. Res.* **116** G03004

Kendall A 2014 Climate change mitigation: deposing global warming potentials *Nat. Clim. Change* **4** 331–2

Kubistcheck J 1960 *Lei n° 3.824, de 23 de Novembro de 1960,* Brazil

Kuha J 2004 AIC and BIC: comparisons of assumptions and performance *Sociological Methods Res.* **33** 188–229

Lima I B T 2005 Biogeochemical distinction of methane releases from two Amazon hydroreservoirs *Chemosphere* **59** 1697–702

Malhi Y, Baldocchi D D and Jarvis P G 1999 The carbon balance of tropical, temperate and boreal forests *Plant Cell Environ.* **22** 715–40

Malhi Y, Roberts J T, Betts R A, Killeen T J and Li W 2008 Climate change, deforestation, and the fate of the Amazon *Science* **319** 1–5

MME (Ministério de Minas e Energia) EPE (Empresa de Pesquisa Energética) 2013 *Plano Decenal de Expansão de Energia 2022* pp 1–410

MME (Ministério de Minas e Energia) EPE (Empresa de Pesquisa Energética) 2014 *Plano Decenal de Expansão de Energia 2023* pp 1–434

Moomaw W, Burgherr P, Heath G, Lenzen M, Nyboer J and Verbrugge A 2011 *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* Cambridge University Press

Peters G P, Aamaas B, T Lund M, Solli C and Fuglestvedt J S 2011 Alternative 'global warming' metrics in life cycle assessment: a case study with existing transportation data *Environ. Sci. Technol.* **45** 8633–41

Rasera M de F F L, Ballester M V R, Krusche A V, Salimon C, Montebelo L A, Alin S R, Victoria R L and Richey J E 2008 Estimating the surface area of small rivers in the Southwestern Amazon and their role in $CO_2$ outgassing *Earth Interact.* **12** 1–16

Rasera M de F F L, Krusche A V, Richey J E, Ballester M V R and Victoria R L 2013 Spatial and temporal variability of $pCO_2$ and $CO_2$ efflux in seven Amazonian Rivers *Biogeochemistry* **116** 241–59

Richey J E, Melack J M, Aufdenkampe A K and Hess V M B L L 2002 Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric $CO_2$ *Nature* **416** 1–5

Roland F, Vidal L O, Pacheco F S, Barros N, Assireu A, Ometto J P H B, Cimbleris A C P and Cole J J 2010 Variability of carbon dioxide flux from tropical (cerrado) hydroelectric reservoirs *Aquatic Sci.* **72** 283–93

Rosa L P, dos Santos dos M A, Matvienko B, Santos E O and Sikar E 2004 Greenhouse gas emissions from hydroelectric reservoirs in tropical regions *Clim. Change* **66** 9–21

Saatchi S S, Houghton R A, Alves D and Nelson B 2008 *LBA-ECO LC-15 Amazon Basin Aboveground Live Biomass Distribution Map: 1990–2000* Oak Ridge National Laboratory Distributed Active Archive Center (https://daac.ornl.gov/LBA/guides/LC15_AGLB.html)

Salimon C, Santos S E, Alin S R, Krusche A V and Ballester M V 2012 Seasonal variation in dissolved carbon concentrations and fluxes in the upper Purus River, Southwestern Amazon *Biogeochemistry* **114** 245–54

Santos dos M A, Rosa L P, Sikar B, Sikar E and Santos E O 2006 Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants *Energy Policy* **34** 481–8

Sawakuchi H O, Bastviken D, Sawakuchi A O, Krusche A V, Ballester M V R and Richey J E 2014 Methane emissions from Amazonian rivers and their contribution to the global methane budget *Glob. Change Biol.* **20** 2829–40

Shine K P, Fuglestvedt J S, Hailemariam K and Stuber N 2005 Alternatives to the global warming potential for comparing

climate impacts of emissions of greenhouse gases *Clim. Change* **68** 281–302

Shine K P 2009 The global warming potential—the need for an interdisciplinary retrial *Clim. Change* **96** 467–72

St. Louis V L S, Kelly C A, Duchemin É, Rudd J W M and Rosenberg D M 2000 Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate *BioScience* **50** 766–75

StrašKraba M 1973 Limnological basis for modeling reservoir ecosystems *Man-Made Lakes* (*Geophysical Monograph Series* vol 17) (New York: Wiley) pp 517–35

Straškraba M, Tundisi J G and Duncan A 1993 State-of-the-art of reservoir limnology and water quality management *Comparative Reservoir Limnology and Water Quality Management* **77** 213–88

Teodoru C R *et al* 2012 The net carbon footprint of a newly created boreal hydroelectric reservoir *Glob. Biogeochemical Cycles* **26** GB2016

Tundisi J G, Matsumura-Tundisi T and Calijuri M C 1993 Limnology and management of reservoirs in Brazil *Comparative Reservoir Limnology and Water Quality Management* **77** 22–55

Wehrli B 2011 Climate science: renewable but not carbon-free *Nat. Geosci.* **4** 585–6